The Relation Between Forest Structure and Soil Burn Severity

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***Abstract**—A study funded through National Fire Plan evaluates the relation between pre-wildfire forest structure and post-wildfire soil burn severity across three forest types: dry, moist, and cold forests. Over 73 wildfires were sampled in Idaho, Oregon, Montana, Colorado, and Utah, which burned between 2000 and 2003. Because of the study's breadth, the results are applicable for understanding how forest structure relates to post-wildfire soil burn severity within Rocky Mountains forests. This paper discusses a burn severity classification that integrates fire intensity, fire severity, and post wildfire response; and discusses the relations wildfire setting (fire group), tree crown ratio, tree canopy cover, surface fuel condition, and tree size have with different soil burn severity outcomes.*

Introduction

Although canopy bulk density, fuel models, canopy base height, and other forest metrics have been related to fire behavior using physical laws, controlled experiments, and models (Graham and others 2004, Peterson and others 2005), there is limited information to indicate how forest structure influences or is related to burn severity (what is left and its condition) after a wildfire event (Broncano and others 2004, Loehle 2004, Weatherspoon and Skinner 1995). Moreover, the uncertainty of these relations is unknown, preventing forest managers from communicating their confidence in fuel treatments that may reduce the risk of wildfires and their effects. Without these estimates, managers and forest stakeholders could have a false sense of security and a belief that if a wildfire occurs after a fuel treatment the values they cherish (for example, homes, wildlife habitat, community water sources, sense of place) will be protected and maintained both in the short- (months) and long- (10s of years) term.

In 2001, we began to define and quantify the relation between forest structure and soil burn severity and determine the uncertainty of the relations (Jain and Graham 2004). Although other studies have quantified this relationship they often were limited in scope and applicability (Cruz and others 2003, Martinson and Omi 2003). To avoid these shortcomings, we designed our study to sample many different wildfires (73) that burned throughout the inland western United States over multiple years. Because of the study's scope, it incorporated a large amount of variation in forest structure as well as disparity in burn severity after extreme wildfires. The data we collected came from wildfires that burned in the moist, cold, and dry forests between 2000 and 2003. By including wildfires that burned throughout the inland

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western United States occurring over multiple years, we were able to include a variety of weather (that occurred during the fires) and physical settings in our sampling. The relations between forest structure and soil burn severity and the uncertainty of these associations after intense and severe wildfires will provide information that can be used for informing fuel management decisions throughout the moist, cold, and dry forests of the inland western United States.

Methods

We visited 73 areas in Montana, Idaho, Colorado, Oregon, Utah, and Arizona burned by wildfires between 2000 and 2003 (fig. 1). These wildfires occurred in three forest cover types: dry (ponderosa pine, *Pinus ponderosa* and Douglas-fir, *Pseudotsuga menziesii*), moist (western hemlock, *Tsuga heterophylla*, western redcedar, *Thuja plicata*, grand fir, *Abies grandis*, white fir, *Abies concolor*) and cold (lodgepole pine, *Pinus contorta* and subalpine fir, *Abies lasiocarpa*) forests throughout the inland western United States. Since not all forest burned in a single year, we included multiple years and multiple geographic regions in our data collection (fig. 1). All areas were sampled the summer after they burned, except areas in Flathead and Lincoln counties in Montana and the Diamond Peak complex of fires in Idaho, which burned in 2000. These wildfires were sampled the second summer after they burned.

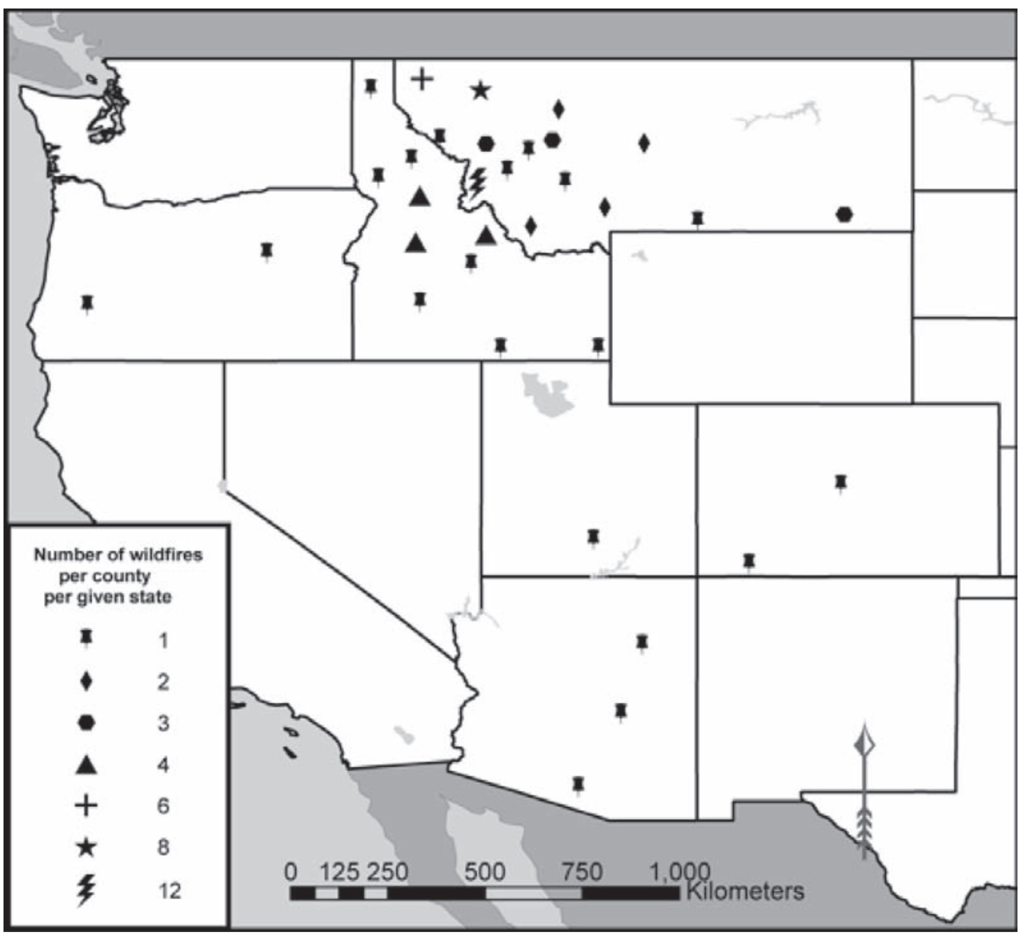

Figure 1—Distribution of the seventy-three wildfires sampled between 2001 and 2004.

Sampling Designs

We used three sampling designs to capture the variation in burn severity occurring at different spatial scales. Intensive sampling occurred in 28 wildfires that burned between 2000 and 2003. Extensive sampling revisited previously established Forest Inventory and Analysis (FIA) plots within 61 wildfires that burned in Montana and Idaho in 2000 and those burned in Montana during 2001 and two wildfires were visited using focused watershed (142 ha to 6,480 ha) sampling.

Intensive Sampling

For each selected wildfire (28 fires), we used stratified random sampling to ensure the variation in forest structure, physical setting, and weather were represented. Our sampling stratification began with forest cover (dry, moist, and cold), followed by burning index (two classes), slope angle (two classes), canopy height (two classes), and stand density (two classes). In establishing the sampling frame, forest cover type described the broad-scale vegetation. We used fire progression maps, local weather data, and the most applicable fuel model for each stand within a fire perimeter to calculate Burning Index (Bradshaw and Britton 2000). We split our sampling at the median burning index for all stands burned by a particular wildfire. The physical settings of the stands were placed into two strata: those with slope angles less than or equal to 35 percent and those with slope angles greater than 35 percent. The Hayman fire in Colorado and Flagtail fire in Oregon had moderately steep topography where we used a 25 percent slope angle to differentiate the two classes. Nested within slope class, stands were divided into sapling to medium sized trees ($\leq$12.5 m) and mature to old trees (>12.5 m). Within height class, two density stratum were identified: those with canopy cover $\leq$35 percent and those with canopy cover >35 percent. All stands within a fire perimeter had an equal probability of being selected. We randomly selected a stand if it 1) met the sampling criteria, 2) had an opportunity to burn, 3) did not have any confounding factors (evidence of suppression activities), and 4) was at least 100 m by 100 m in size.

Extensive Sampling

Interior West Forest Inventory and Analysis staff have randomly located permanent forest sample plots throughout the forests of the western United States. Several of these plots burned in 2000 and 2001 (61 wildfires). Wildfires that burned in Idaho and Montana in 2000, all wildfires that burned in Montana in 2001, and the wildfires that burned in Utah and Arizona in 2003 were revisited. Because FIA plots were distributed across spatially defined grids and the burned areas varied in size and location, the number of plots burned by the fires varied considerably. As a result, some burned areas had multiple FIA plots sampled after a wildfire while other areas only had one plot revisited.

Focused Watershed Sampling

The focused watershed sampling occurred within forests burned by the Quartz and Diamond Peak fire complexes in Idaho and Oregon in 2000 and 2001. Using GIS based maps, we delineated the watersheds burned by these two wildfire events and subsequently defined a 60-m riparian zone along each side of the stream reaches. Areas outside the riparian zone within each watershed were defined as the upland zone. A minimum of twenty-five plots were randomly located within both the upland and riparian zones using a complete spatial randomness (CSR) Poisson process (Diggle 2003). Using this approach, spatial autocorrelation was avoided (Cressie 1991).

Data Collection

Our intention was to develop a continuous variable or post classify the burn severity of the forest floor. To do so, fine resolution descriptors of soil burn severity were synthesized from past burn severity characterizations to develop the burn severity indicators. Our soil burn severity concentrated on what was left after the fire and not what was consumed (DeBano and others 1998, Key and Benson 2001, Ryan and Noste 1985, Wells and others 1979). For each randomly located plot, physical setting descriptors (aspect, slope angle, topographic position, and elevation), a general stand description (species composition, number of stories, and horizontal spacing), and stand origin (past harvest evidence and regeneration treatment) were recorded. Forest floor characterization included total cover and the proportion of total cover dominated by each char class (unburned, black, grey, or orange colored soils) on a fixed radius plots (1/741 ha). These included new litter (deposition since the fire), old litter (present previous to the fire), humus, brown cubical rotten wood (rotten wood at or above the soil surface), woody debris less than or equal to 7.6 cm in diameter, woody debris greater than 7.6 cm in diameter, rock, and bare mineral soil.

Physical Setting, Fire Weather, and Forest Structure—Fire behavior and burn severity, for the most part, are determined by physical setting (location, topography, juxtaposition, and so forth), fuels (live and dead vegetation), and weather (both short- and long-term). We used the individual fire to reflect the broad scale physical setting. For each burned area we obtained hourly weather observations that occurred during the wildfire. Data from remote automatic weather stations (RAWS) located in the county where each wildfire burned were summarized into daily reports using Fire Family Plus 3.0 (Bradshaw and McCormik 2000). The weather data included relative humidity, maximum temperature, wind speed, and fuel moistures of 1-, 10-, 100-, and 1000-hour fuels. Because the exact day and time a specific plot burned was undetermined, we summarized the weather data to the specific fire. Weather data was unobtainable for some fires located in remote wilderness areas (4 fires).

We used the Forest Vegetation Simulator (FVS) and its Fire and Fuels Extension (FFE) to characterize pre-wildfire forest structure (Wykoff and others 1982, Reinhardt and Crookston 2003, Dixon 2004). Forest structure characteristics included stand density indices, characteristics associated with fire behavior (surface fuels, canopy bulk density, canopy base height), and other miscellaneous stand characteristics (Reinhardt and Crookston 2003). In addition to these FFE-FVS derived forest characteristics we estimated canopy base height directly from our data and described total cover which included canopy overlap as suggested by Crookston and Stage (1999). Also, rather than using quadratic mean diameter (QMD) to describe stem dimensions, we used stem diameter at breast height (d.b.h.) (1.4 m) weighted by basal area[1].

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[1] Basal area weighted diameter breast height (d.b.h.-in) is $\sum$ ((d.b.h.*individual tree basal area (ft^2) * number of trees for each d.b.h. class) divided by $\sum$ (number of trees * individual tree basal area (ft^2).

There are several ways to characterize overstory density such as basal area per unit area, trees per unit area, percent cover, canopy bulk density, relative stand density index, total cubic volume per unit area, and total standing biomass. To avoid collinear variables as predictors, we used canonical correlation for data mining and our expertise to determine which variables had promise for identifying the relation between forest structure and soil burn severity. For density we chose total canopy cover with overlap, for tree size we used basal area weighted d.b.h., average height, and species composition was broadly defined as dry, moist, or cold forest. To describe the forest canopy we used canopy base height (total height minus uncompacted crown length then averaged for plot), and uncompacted crown ratio (fig. 2).

Classifying Burn Severity—Figure 3 illustrates a model we used to develop our soil burn severity classification. The fire literature provided knowledge on fire intensity by describing the heat pulse into the soil (for example, Baker 1929, Debano and others 1998, Hungerford and others 1991, Wells and others 1979). However, the amount of fuel consumed by a fire event also reflects fire intensity. Therefore, we incorporated fire severity into our burn severity classification (for example, Debano and others 1998, Key and Benson 2001, Ryan and Noste 1989) and finally, we included ecological responses

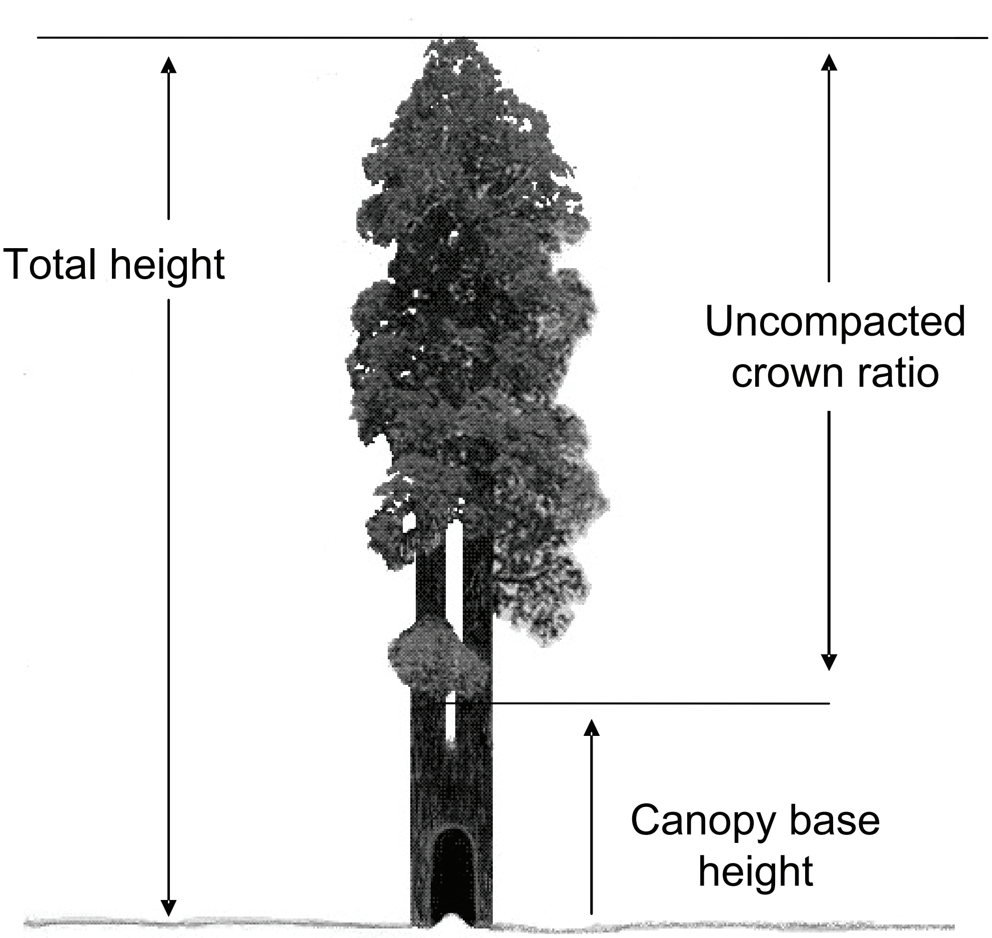

Figure 2—Illustration of how we measured uncompacted crown ratio and canopy base height (total height minus length of uncompacted crown ratio).

that likely occur after a wildfire (for example, changes in wildlife habitat, alterations in soil productivity, changes in soil erosion potential) (Debano and others 1998, Neary and others 1999). As a result our soil burn severity (what is left) classification linked fire intensity, fire severity, and the ecological response (fig. 3).

The classification included six levels of soil burn severity (fig. 4). The factors in the soil burn severity include proportion of litter, mineral soil, and exposed rock present after a fire and their dominant char class, defined as unburned, black char specific to mineral soil, and gray and orange char specific to mineral soil (Wells and others 1979, Ryan and Noste 1989, Debano and others 1998) (fig. 4). The soil burn severity levels included: 1) sites that contained greater than 85 percent litter cover, all char classes, 2) 40 to 85 percent litter cover, all char classes, 3) less than 40 percent litter cover and mineral soil is dominated by black char, 4) less than 40 percent litter cover and mineral soil is dominated by grey or white char, 5) and mineral soil is dominated by black char and no litter cover, and 6) no litter cover and mineral soil is dominated by grey or white char (fig. 4). Wildfires and their “goodness,” or lack there of, depends on the values at risk and the biophysical setting and the management

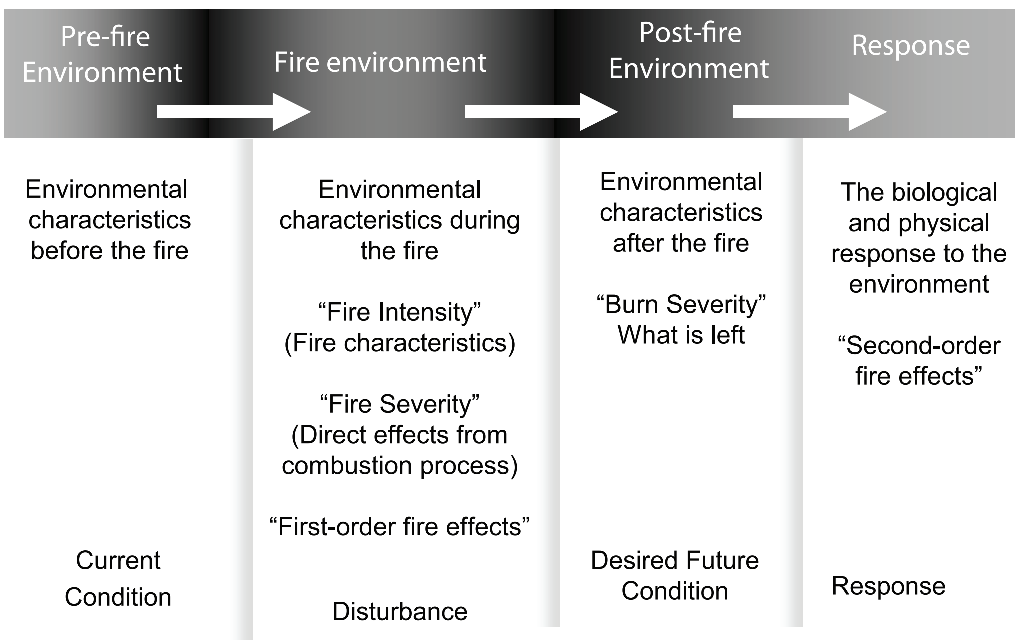

Figure 3—The fire disturbance continuum, of which there are four components, describes the interpretation of different factors involved in wildfires (Jain and others 2004). The first component, the pre-fire environment, includes forest vegetation and state of the environment (moisture levels, amount of biomass, and species composition). This can also be referred to as the current condition just prior to the fire event. The second component, the fire environment, is the environment during the fire event, where fire intensity and fire behavior are characterized in addition to fire severity. Changes to forest components from the fire are also referred to as first-order fire effects. The third component is the environment after the fire is out, referred to as the post-fire environment. This is the environment created by the fire but also is a function of the pre-fire environment and is characterized by what is left after the fire. We refer to this as burn severity. In some cases when fuel treatments are being applied to create a more resilient forest, this could be referred to as the desired condition. The last component is the response, often referred to as second-order fire effects.

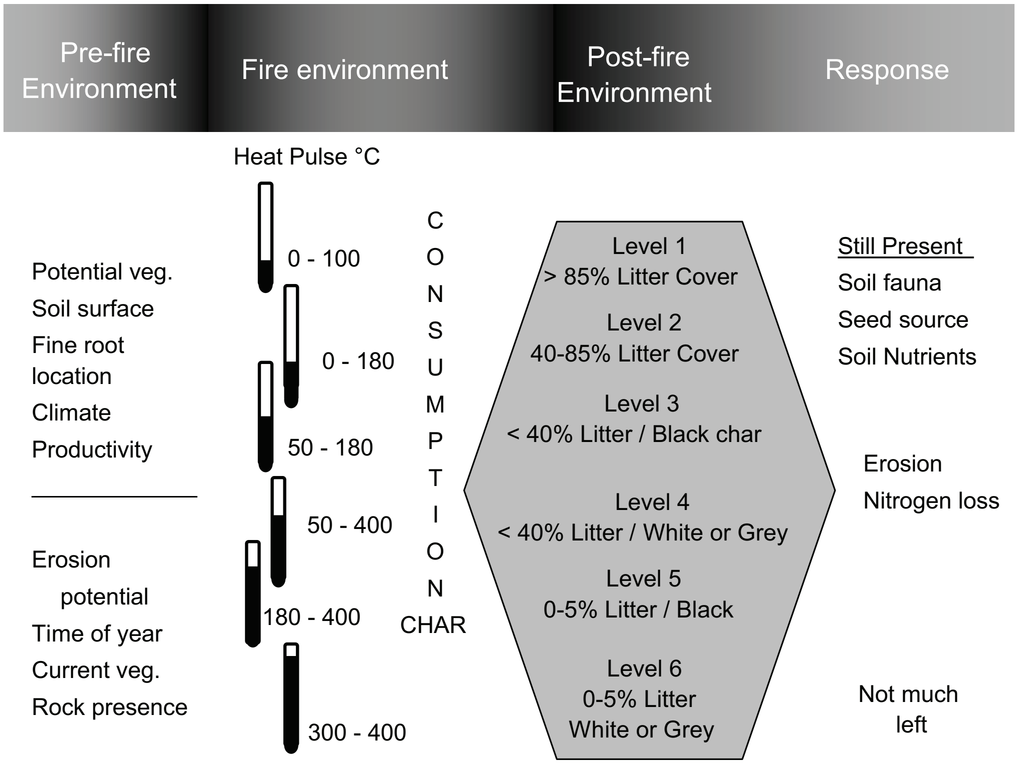

Figure 4—Within the post-fire environment, the soil burn severity classification includes six levels. Going from left to right, a range of temperatures associated with the fire event correspond to the probable indicator of what is left after a fire. For example, to maintain litter cover, the heat pulse into the ground had to be between 0 and 1000 °C. When surface litter is left, often soil fauna are still alive, which often occurs when within a fire severity context, a possible description, is less than 15% of surface litter is consumed. In contrast, by level 6 soil burn severity, the heat pulse into the ground had to exceed 3000 °C in order to create white ash or a grey charred soil appearance (Hungerford and others 1991). The char in each burn severity level refers to the dominant char present after the fire.

objectives for a given setting. Therefore, our six levels of soil burn severity do not depict a value but rather describe a continuum from an unburned forest floor to one in which fire has appreciably altered the physical and biological conditions of the forest floor.

Analysis and Interpreting Results

We combined our six levels of soil burn severity into three levels to ensure our observations were relatively evenly distributed among the different severity classes. Level 2 burn severity (combined level 1 and 2, fig. 4) consisted of areas with greater than 40 percent litter cover ,and the forest floor could vary from unburned to areas exhibiting black char. Level 4 (combined levels 3 and 4, fig. 4) soil burn severity described areas where less than 40 percent litter cover existed and the exposed mineral soil was either black or grey in color. Level 6 soil burn severity (combined levels 5 and 6, fig. 4) described sites where there was minimal litter cover and the exposed mineral soil was black, gray and/or orange colored, or there was an abundance of exposed rock.

We identified relations between forest structure and soil burn severity using a nonparametric classification and regression tree technique (CART) (Breiman and others 1984, Steinberg and Colla 1997). Figure 5 shows a thirteen-outcome classification tree predicting soil burn severity as a function of pre-wildfire forest structure. Outcomes 1 through 13 (shaded) show number of observations correctly classified, total number of observations, and the conditional probability of certainty. Forest characteristics occurring at the top of a classification tree were clearly related to burn severity compared to characteristics that appeared later in the tree. For example, wildfire groups (groups of individual fires) were often the most important in differentiating soil burn severity, followed by uncompacted crown ratio, total cover, and weighted basal area d.b.h. (fig. 5). In addition, the classification tree identified thresholds

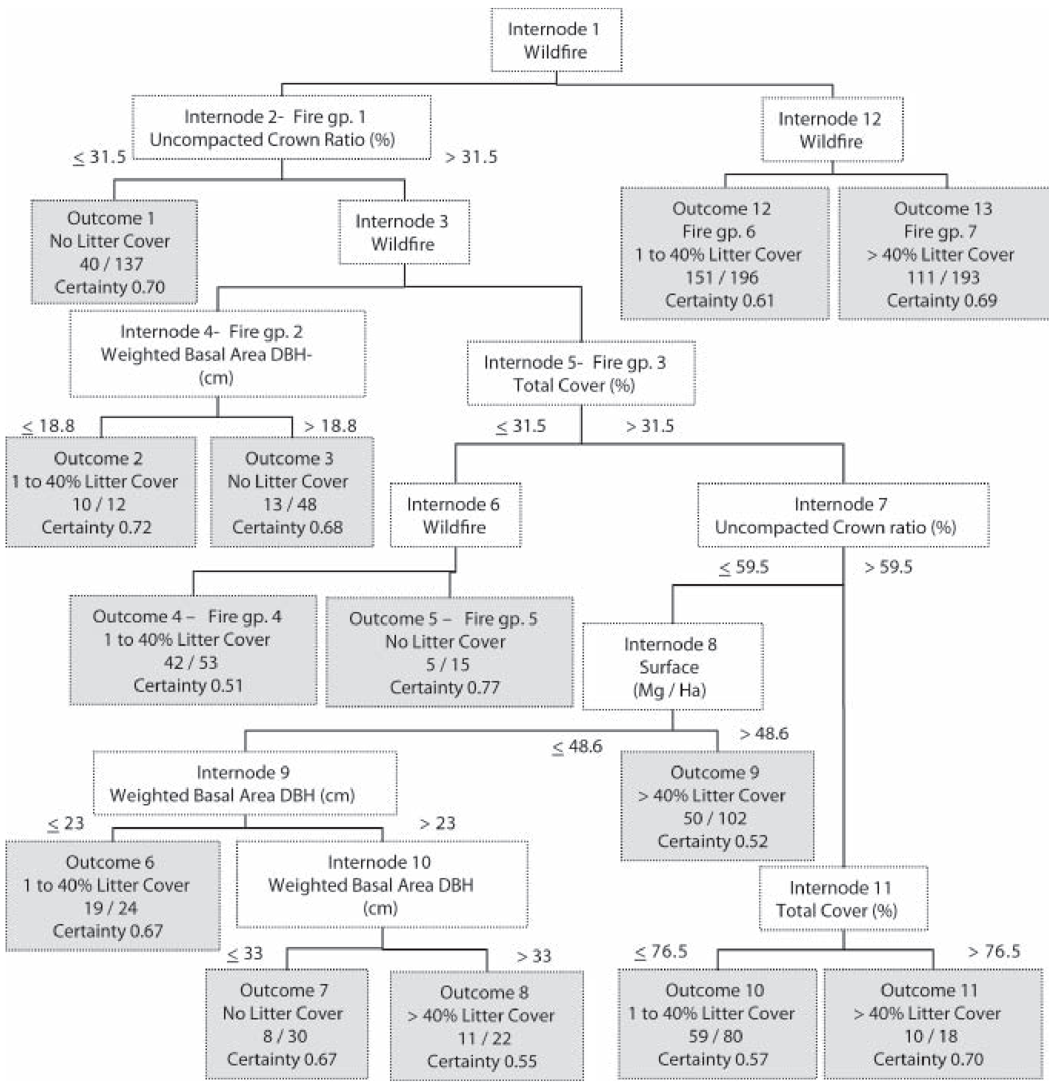

Figure 5—Classification tree for predicting soil burn severity resulting from CART analysis. Shaded areas reflect different predicted outcomes. Each outcome contains the soil burn severity, the number of correctly classified observations versus the total number of observations in the outcome and a conditional probability referred to as "certainty." The internode is where splits occurred based on either fire group or forest structure threshold. Numbers to the left and right of the node indicate the forest structure threshold used in predicting a particular outcome.

at which a forest structure characteristic became related to soil burn severity. In our classification, trees with uncompacted crown ratios ≤31.5 percent were highly related to low litter soil burn severities (level 6, outcome 1) (fig.5). In contrast, trees with uncompacted crown ratios >31.5 percent, differentiated (internode 3) into several outcomes (2 – 8) later in the CART classification. The CART analysis displays conditional probabilities (certainty) of an event happening predicated on earlier classifications. For example, the 0.70 probability of soil burn severity level 6 occurring in outcome 1 is dependent not only if trees have uncompacted crown ratios ≤31.5 percent but also the condition needs to occur within fire group 1 (fig. 5).

Results and Discussion

Our results show that soil burn severity (what is left after a wildfire) is strongly related to general wildfire conditions. That is, we identified seven groups of fires showing similarities when related to soil burn severity (fig. 5). The strength of these relations is exemplified in that fire group 7 only (1 outcome) contained sites with level two soil burn severity (> 40% litter cover, outcome 13). Similarly, fire group 6 only contained sites with level 4 soil burn severity (1 to 40% litter cover, outcome 12). The 56 wildfires in these two groups predominantly burned in the moist and cold forests (figs. 5, 6).

The wildfires in group 3 (outcomes 4 – 11) by far had the greatest diversity in soil burn severity of the wildfires we visited, and the stand structural characteristics often influenced the soil burn severity. Within this fire group total stand cover (internode 5, 31.5%, fig. 5) was an important soil burn severity differentiating characteristic. Stands with the lower canopy covers (≤31.5%) differentiated into two additional fire groups (internode 6, fire groups 4 and 5) and resulted in level 4 (1 to 40% litter cover, outcome 4) and level 6 (no litter cover, outcome 5) soil burn severities (fig. 5). Several of the soil burn severity outcomes (6 – 8) occurring in fire group 3 were related to tree size (weighted d.b.h.) and surface fuel amounts (fig. 5). The wildfires creating these burn severities tended to occur in the dry forests (fig. 6). Also within fire group 3 total cover (internode 11), after uncompacted crown ratio (internode 7), became an important structural element influencing soil burn severity (fig. 5). That is, stands burned in the moist and cold forests with total cover less than 76.5 percent tended to have level 4 (1 to 40% litter cover) soil burn severity and stands having excess of 76.5 percent cover tended to have level 2 soil burn severity (>40% litter cover) (fig. 5). These outcomes (10 and 11) most frequently occurred when wildfires burned the moist and cold forests (figs. 5, 6).

The differentiation of soil burn severity as a result of fire group most likely reflects wildfire characteristics such as fire duration, surface fuel moistures, heat produced, physical setting (for example slope angle, aspect), and geographic location (elevation, landscape position, watershed orientation and juxtaposition). In addition, these results emphasize the importance of observing many wildfires occurring in different years (weather), among many forest types (composition, potential vegetation), and across geographical areas (for example, northern Rocky Mountains, central Rocky Mountains) in order to understand the relation between wildfires and forest structure and how they may determine soil burn severity (Van Mantgem and others 2001).

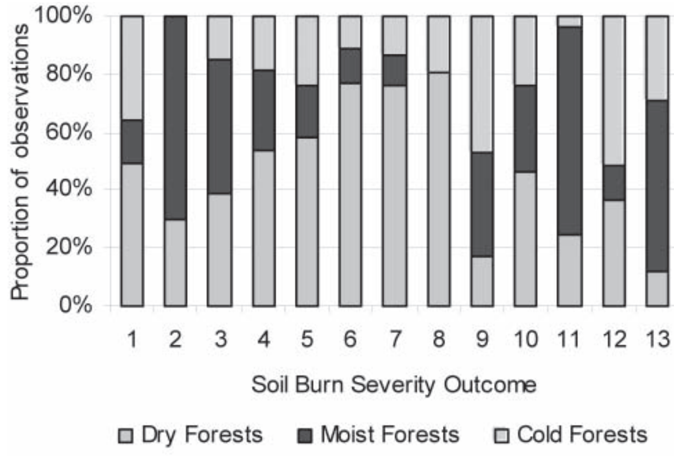

Figure 6—The distribution of forest type within each soil burn severity outcome (see fig. 5). Dry forests are ponderosa pine and/or Douglas-fir cover type. Moist forests are either western hemlock, grand fir, western redcedar, or white fir cover types. Cold forests are subalpine fir and/or lodgepole pine cover types.

Canopy base height, uncompacted crown ratio, and surface fuel conditions most often determine whether a fire will transition from the surface to a crown fire and as a result determine tree burn severity (Scott and Reinhardt 2001, Graham and others 2004, Peterson and others 2005). In contrast, soil burn severity depends on the amount of heat generated on the soil surface, the conduction of heat into the soil layers, and the heat's duration (DeBano and others 1998, Neary and others 1999, Wells and others 1979). These processes are strongly related to the amount of surface fuels, their structure and composition, their moisture content, the pre-fire environment, and the fire environment (fig. 4). Stand characteristics such as tree canopy cover, canopy cover distribution, uncompacted tree crown ratio, and forest composition interact and influence the amount, composition and distribution of live and dead ground-level vegetation (Barnes and others 1998, Oliver and Larson 1990). Therefore, we were not surprised that within a fire group, the most common forest characteristics related to soil burn severity were uncompacted crown ratio, (internodes 2, 7), total cover (internodes 5, 11), tree size (internodes 4, 9, 10), and the amount of surface fuels (internode 8) (fig. 5). Often, these forest characteristics worked in concert and hierarchically to produce a given soil burn severity. For example, for burned over soils to exhibit a level two burn severity (outcome 9) was predicated on sites occurring within fire group 3, trees on the site containing uncompacted crown ratios between 41.5 and 59.6 percent, total canopy cover on the site was less than 31.5 percent, and the surface fuel amounts had to exceed 49.6 Mg ha^{-1} (fig. 5). These results illustrate how overstory characteristics can influence soil burn severity within a group of wildfires and most likely these soil burn severities were related to the amount and condition of ground-level vegetation present when the wildfires burned.

The length of tree crowns in relation to the height of the trees (crown ratio) surprisingly had a strong (differentiated early in the CART analysis) association with soil burn severity, especially with wildfires occurring in group 1 (fig. 5, outcome 1). Fires burning stands with uncompacted crown ratios $\leq$31.5 percent tended to have no litter cover left after the fires burned, resulting in a level 6 soil burn severity (fig. 5). Many of the stands having this soil burn severity were multi-storied (60 of 127 sites had 3 stories or more) with Douglas-fir trees dominating the dry forests and lodgepole pine trees dominating the cold forests. The trees burned had high canopy base heights (>10 m), the stands averaged 1,900 trees ha^{-1} ($S_{\bar{x}}$ = 196), the mean canopy cover was 40 percent ($S_{\bar{x}}$ = 3) and tree diameter (weighted basal area d.b.h.) was less than 19 cm ($S_{\bar{x}}$ = 1). These results suggest that stands containing trees with short crowns occurring primarily in the cold and dry forests most likely influenced the composition, amount, distribution, structure, and moisture content of the surface fuels. The relatively high tree density may have suppressed surface wind speeds, favoring slow fire spread rates that could have combined with the ground-level vegetation conditions and forest floor surface layers (duff) to favor long duration surface fires. These burning conditions are often attributed to leaving no surface organic matter on a site after a fire and creating black or grey colored mineral soil (Debano and others 1998, Key and Benson 2001, Ryan and Noste 1989).

Stands within fire group 1 and containing trees with uncompacted crown ratios exceeding 31.5 percent differentiated into a multitude of soil burn severities depending on further fire groups, tree diameter, canopy cover, and surface fuel amounts. Within fire group 1 soil burn severity was related to total canopy cover in a subset of wildfires (internode 5, group 3). When burned, the denser stands (cover >76.5%) with crown ratios exceeding 59.5 percent tended to have greater than 40 percent litter cover or level two soil burn severity (outcome 11, fig. 5). Stands exhibiting this soil burn severity usually contained 3 or more canopy layers with mean canopy cover exceeding 90 percent ($S_{\bar{x}}$ = 3) and canopy base heights exceeding 4 m ($S_{\bar{x}}$ = 0.6). This soil burn severity most often occurred within moist forests which tend to have high moisture contents in the surface fuels as a result of the deep and closed canopy conditions. In fact the 1000-hour fuel moisture contents occurring in stands exhibiting this soil burn severity averaged 15.5 percent and were greater than those observed in stands exhibiting the other outcomes (fig. 7). These results indicate that apparently because of the high fuel moistures, moist forests can be relatively resilient to wildfire, even if they contain multiple canopy layers, dense canopy cover, and low canopy base heights.

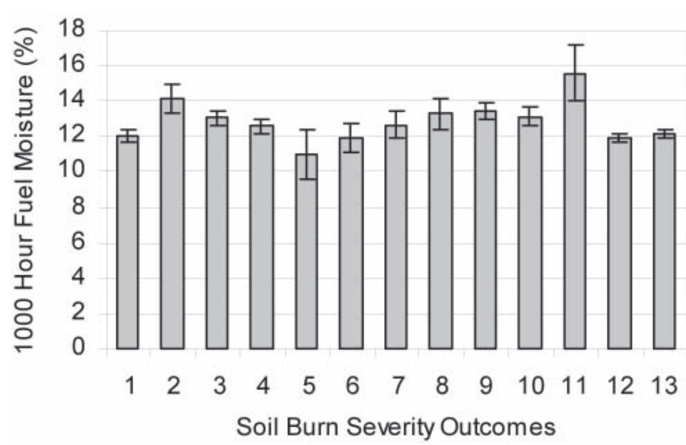

Figure 7—Average fuel moisture and standard errors for the 1000-hour fuels occurring in the stands for each soil burn severity outcome (see fig. 5).

Tree crown ratio appears to influence many stand characteristics that relate to soil burn severity and its influence varies by fire group and canopy cover. After uncompacted crown ratio and canopy cover, the amount of surface fuel becomes influential in determining soil burn severity. However the larger amounts of surface fuels do not readily translate into greater soil burn severity when the forests burned. For example, when wildfires burned stands with crown ratios exceeding 31.5 percent and less than 59.5 percent, canopy cover exceeding 31.5 percent, and containing surface fuels in excess of 48.6 Mg ha^{-1}, level 2 soil burn severity (>40% litter cover) was observed (outcome 9, fig. 5). The moist and cold forests typified this outcome, which historically tend to accumulate large amounts of surface woody debris (80 Mg ha^{-1}, $S_{\bar{x}}$ = 2.5).

After uncompacted crown ratio, canopy cover and the amount of surface fuel, tree size (d.b.h.) becomes a determinant of soil burn severity. The dominance of large trees on a site appear to create conditions that moderate soil burn severity. Soil burn severity level 2 was observed in stands that were dominated by large trees (46 cm, $S_{\bar{x}}$ = 1.0 basal area weighted d.b.h.) even though they contained an average of 40 Mg ha^{-1} ($S_{\bar{x}}$= 0.6) of surface fuels (outcome 8, fig. 5). The canopy cover was moderate (60%, $S_{\bar{x}}$ = 3), as was the canopy base height (7 m, $S_{\bar{x}}$ = 0.6) of stands exhibiting this soil burn severity. This outcome was distributed across the dry forests in strands containing tree densities ranging from 700 to 2,100 trees ha^{-1}. In contrast, level 6 (no litter cover) soil burn severity was observed in predominantly dry forest stands similar to those occurring in outcome 8, except tree diameters were less than or equal to 33 cm. Stands exhibiting this burn severity averaged 28 cm (weighted by basal area) in diameter and contained 1,000 to 2,200 trees ha^{-1}. The mean canopy cover of the stands was 61 percent and the tree canopy base height averaged 4 m ($S_{\bar{x}}$ = 0.5).

These two contrasting soil burn severity outcomes differentiated by tree diameter most likely are related to the tree juxtaposition and variation in density of trees occurring within the stands, especially in ponderosa pine forests, large trees tend to be distributed irregularly often occurring in clumps (Graham and Jain 2005). This irregular horizontal structure would tend to perpetuate variable surface fuel amounts and create a diverse fuel matrix. As a result, surface fires burning fuels in these conditions would most likely result in variable soil burn severities which on the average would be low (level 2). However, small diameter (for example 28 cm) and most likely mid-aged stands, particularly when excluded from fire, tend to develop with more horizontally uniform distributions. As a result, the surface fuels and burning conditions would also be uniform in these stands and may have resulted in surface fires with long residence times.

Small trees (d.b.h.), after uncompacted crown ratio, canopy cover, and the amount of surface fuel were related to level 4 soil burn severity (fig. 5, outcome 6). The dry forest stands dominating this outcome (fig. 5, outcome 6) had 62 percent canopy cover, which was similar to that of the stands occurring in outcomes 7 and 9, but the stands contained more trees (2,000 to 2,800 trees ha^{-1}). Canopy base heights were relatively low (2 m) and average tree height was 13 m ($S_{\bar{x}}$= 1).

The range of soil burn severities occurring among outcomes 6, 7, and 8 illustrate how stand development within dry forests influences soil burn severity. The small diameter young forests when burned tended to create level 4 soil burn severities (outcome 6), the stands with mid-sized and likely mid-aged trees when burned tended to create level 6 soil burn severities (outcome 7, fig. 5), and when stands containing large and old trees burned, level 2 soil burn severities were created (outcome 8, fig. 5).

In fire group 2, which is a subset of group 1 fires, tree size was second only to uncompacted crown ratio in explaining soil burn severity. Again, diameter most likely reflects a developmental stage of the stands exhibiting the two contrasting burn severities. Stands with the smaller and younger trees (<18.8 cm, weighted basal area d.b.h.) had level 4 burn severity compared to the stands containing the mid-aged and larger trees (>18.8 cm weighted basal area d.b.h.) which exhibited level 6 burn severity (no litter). These findings were similar to those illustrated in outcomes 6 and 7 except these outcomes occurred in fire group 2 and outcomes 6 and 7 occurred in fire group 3 (fig. 5). The moisture content of the 1000-hour fuels in stands occurring in outcome 2 was 14 percent ($S_{\bar{x}}$ = 1) and 11 percent ($S_{\bar{x}}$ =1) for the 1000-hour fuels within stands occurring in outcome 3.

Thinned stands, plantations, and others exhibiting management typified stands in outcomes 2 and 6. The forest floor conditions of stands in these outcomes most likely resembled those associated with stand initiation structural stages. These early structural stages frequently contain moist and robust layers of ground-level vegetation. Because these stands were managed, the surface fuel matrix was modified through slash disposal and site preparation activities resulting in a discontinuous fuel bed. Particularly, in the cold and moist forests, crown fires would burn around these areas and most often there was evidence that firebrands landed in these stands but the surface fuel conditions prevented sufficient fire from developing that could create a smoldering fire. Therefore, these results indicate that high stand densities and low canopy base heights do not necessarily lead to severely burned soils and other factors such as developmental stage may also influence soil burn severity.

After uncompacted crown ratio (>31.5%) and total canopy cover (<31.5%) the fire setting (fire group) became an important predictor of soil burn severity (fig. 5). Two fire groups differentiated, one expressing level 4 soil burn severity (outcome 4, fire group 4) and one expressing level 6 soil burn severity (outcome 5, fire group 5). Both outcomes had similar representation from cold, moist and dry forests (fig. 6) and the stand densities of both were low (292 trees ha^{-1} for outcome 4 and 312 trees ha^{-1} for outcome 5) when compared to stand densities occurring in the other outcomes. Also, for both outcomes canopy base heights were near 6 m and the uncompacted crown ratios for both were above 60 percent. The greatest difference in the stands occurring in the two outcomes was the setting (for example topography, geographic location, watershed juxtaposition and so forth) in which they occurred. Outcome 5 consisted of observations from the Hayman and Missionary Ridge fires in Colorado and the Ninemile fire in Missoula County, Montana. Outcome 4 included observations from the Alpine, Bear, and Blodget fires in Ravalli County, Montana and the Flagtale fire in Grant County, Oregon. The stands burned by wildfires in outcome 4 also had higher 1000-hr fuel moistures (12.5%) than stands burned by the fires in outcome 5 (11%) (fig. 7). In addition, the average wind speeds occurring during the fires in outcome 5 tended to be higher (7 to 8 miles hour^{-1}) when compared to the winds blowing during outcome 4 fires (4 miles hour^{-1}). The different burning conditions (for example fuel moisture, wind speed, location, and so forth) exemplified in these two outcomes probably had a greater influence on soil burn severity than forest structure, given that both outcomes had very similar structural characteristics.

There are several factors (for example, weather, type of vegetation, fuel moisture, atmospheric stability, physical setting, ladder fuels, surface fuels) that influence fire behavior and burn severity, and forest structure is only one (Agee 1996, Graham and others 2004). Therefore, we did not expect forest structure to fully explain all of the variation present in soil burn severity after a wildfire. However, through our study and the analysis we performed, we were able predict soil burn severity as a function of pre-wildfire forest structure with probabilities far greater than what would have occurred randomly. These variables were not only hierarchally related to soil burn severity, but together they very readily predicted three levels of soil burn severities. Because we identified three levels of soil burn severity, a random probability of a given soil burn severity occurring would be 0.33. Therefore, any probability exceeding 0.33 of the complete CART tree correctly classifying a particular soil burn severity indicates the addition of forest structural characteristics were significantly related to soil burn severity. The variables, in order of importance, fire group, uncompacted crown ratio, weighted basal area d.b.h., total cover, and surface fuel amounts classified level 2 soil burn severity (>40% litter cover) with a 0.46 probability, level 4 soil burn severity (1 to 40% litter cover) with a 0.40 probability, and level 6 (no litter cover) soil burn severity with a 0.57 probability.

Conclusion

Undoubtedly intense fire behavior is a primary concern for forest management throughout the western United States and fuel treatments to modify this fire behavior are a primary concern (Graham and other 2004). However, in most circumstances what a fire leaves behind in terms of soils, homes, and trees is as important, if not more important than fire behavior. Therefore, fuel treatments need to be designed and implemented as to modify burn severity and the traditional thinned forest with high canopy base heights may not result in the desired burn severity.

One size does not fit all. Therefore, we would suggest that fuel treatments be designed to consider burn severity as well as fire behavior. In particular, biophysical setting (fire group, forest type, locale, potential vegetation type, and so forth) needs to provide context for planned fuel treatments. Secondly, tree canopy base height (reflected in uncompacted crown ratio) needs to be considered when designing fuel treatments, although high canopy base heights do not always reduce soil burn severity. Similarly, reducing total forest cover does not necessarily reduce soil burn severity; rather its interactions with the biophysical setting, canopy base height, and surface fuel amounts and conditions most likely determine soil burn severity. The last characteristics that we identified as having a relation with soil burn severity, were tree diameter and surface fuel amounts.

The robust data we accumulated from wildfires that burned throughout the western United States in recent years did not greatly simplify our understanding of the relations between forest structure and soil burn severity. Nevertheless, we did identify several interactions between forest characteristics and soil burn severity that have fuel treatment management applications. A significant factor of this work is the estimate of the certainty a forest structure (fuel treatment) will have in modifying soil burn severity. The conditional probabilities (certainty) we identified of forest structure or fire setting (fire group) influencing soil burn severity always exceeded 0.50 and occasionally exceeded 0.75 (fig. 5). In addition, the approach we took in identifying the relations between forest structure and burn severity, and the level of certainty we provided, was conditional on the circumstances in which the forest characteristic occurred. This kind of information will be of value when communicating the importance forest structure (fuel treatments) has on determining the aftermath of wildfires. This paper and the analysis and results we reported are a continuation of our work in understanding how forest structure interacts with wildfires, their biophysical setting, and burning conditions to create a particular burn severity.

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